SILICON CARBIDE THYRISTORS FOR POWER APPLICATIONS

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Abstract

Silicon carbide has the potential to make high-performance power devices. Its high thermal conductivity, wide bandgap, high breakdown field and high saturated electron drift velocity imply a clear superiority over Si and GaAs. This work reports the fabrication and testing of three-terminal 6H-SiC thyristors. The silicon carbide thyristors show higher current density and higher temperature operation than is possible with silicon devices. Switching measurements at room temperature and at elevated temperatures are reported. SiC thyristors have demonstrated 650 V forward blocking voltage, 5200 A/cm^2 current density, 43 ns switching speed, and reliable 300 C operation. The device structures used in this work consist of a pnpn structure made from epitaxial layers grown on n-type 6H-SiC substrates. To improve electrical gating, the low-doped n-type gate region is N ion-implanted. Ohmic contact to the gate is then made using Ni metallization. Ohmic contacts to the p-type anode material and the n-type cathode material are made using Al and Ni (respectively). A recently developed electron cyclotron resonant plasma etching technique is used for gate recess and device isolation etching. Although these are small area devices, their performance demonstrates that power devices with high temperature capability can be made when material quality is sufficiently improved to allow fabrication of larger area devices. Mature devices are expected to find applications in military systems, utilities, and wherever compact thermal management systems or high temperature, high voltage, or high current operation is required.

Introduction

Due to recent advances in processing and fabrication and improvement in material quality, prototype SiC power devices, p-n diodes [1], schottky diodes [2], MOSFETs [3], and thyristors [4-6], have demonstrated higher performance. Silicon carbide bandgap (2.9 eV for 6H-SiC), high thermal conductivity (4.9 W/cm.K), and high avalanche breakdown field (3.3×10^6 V/cm) are particularly advantageous for high power and high temperature devices [7]. Its order of magnitude higher breakdown field than Si, indicates the capability for very high voltage operation (>10 kV), and lower on state resistances at lower voltage. SiC is the most mature of the wide-bandgap materials. In contrast to diamond and GaN, high quality substrates are commercially available, low-resistance ohmic contacts can be made, and material can be doped with both n- and p-type dopants.

Due to its wide bandgap, SiC p-n junctions retain their blocking capability at high temperatures. The temperature at which the intrinsic carrier concentration exceeds 5×10^{15} cm^{-3} is above 1000 C. Leakage current is also very low. SiC p-n diode leakage current at 400 C is less than that of Si diodes at 125 C [8]. Higher device operating temperature can enhance cooling efficiency by allowing a larger temperature differential between device and coolant. Operating temperature for SiC power devices has been estimated to be greater than 550 C [9]. Consequently, the use of SiC power electronics may eliminate or reduce the need for cooling, and increase cooling efficiency. This can result in more compact thermal management systems by eliminating or reducing the size of heat sinks, or possibly eliminating the need for active cooling.

SiC power devices are expected to find application where compact thermal management systems or any of its unique capabilities for high temperature, high voltage, or high current operation are required. Military, utility and aerospace applications present opportunities. Use of SiC devices is likely to become widespread when SiC power

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14. ABSTRACT

Silicon carbide has the potential to make high-performance power devices. Its high thermal conductivity, wide bandgap, high breakdown field and high saturated electron drift velocity imply a clear superiority over Si and GaAs. This work reports the fabrication and testing of three-terminal 6H-SiC thyristors. The silicon carbide thyristors show higher current density and higher temperature operation than is possible with silicon devices. Switching measurements at room temperature and at elevated temperatures are reported. SiC thyristors have demonstrated 650 V forward blocking voltage, 5200 Ncm2 current density, 43 ns switching speed, and reliable 300 C operation. The device structures used in this work consist of a pnpn structure made from epitaxial layers grown on n-type 6H-SiC substrates. To improve electrical gating, the low-doped n-type gate region is N ion-implanted. Ohmic contact to the gate is then made using Ni metallization. Ohmic contacts to the p-type anode material and the n-type cathode material are made using AI and Ni (respectively). A recently developed electron cyclotron resonant plasma etching technique is used for gate recess and device isolation etching. Although these are small area devices, their performance demonstrates that power devices with high temperature capability can be made when material quality is sufficiently improved to allow fabrication of larger area devices. Mature devices are expected to find applications in military systems, utilities, and wherever compact thermal management systems or high temperature, high voltage, or high current operation is required.

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devices perform at higher efficiencies than Si or GaAs devices, and provide more cost-effective operation. High voltage SiC schottky rectifiers may make a significant impact on power electronics in the near term.

Although its chemical stability, mechanical strength, and temperature-resistance are highly desirable for a power device, they lead to difficulties in processing and fabrication. Deep diffusion is not feasible due to low diffusion rates. Ion Implantation, particularly of acceptors, is problematic. Implantation induced damage is difficult to anneal, and implant activation is low. No wet etching technique, suitable for production, exists for SiC. Conventional reactive ion etching suffers from low etch rate, poor selectivity, and causes surface damage due to high substrate bias. Consequently, advancements in processing and fabrication are critical to power device development. We report the successful use of advanced etching, ion implantation, and ohmic contact technology to fabricate a high-current density sensitive-gate 6H-SiC thyristor.

In silicon, thyristor based devices are the choice for high-current, high voltage applications. Regenerative switching and conductivity modulation result in the lowest forward voltage drop of any junction-based switching device, and the lowest conduction loss at high current density. It is expected that SiC thyristor-based devices will retain these same advantages. However, little data has been reported concerning SiC thyristors [4-6]

We report the investigation of 6H-SiC thyristors for high-temperature high-power applications. Switch performance at high temperatures and switching characteristics at high current density have been explored. High frequency operation up to 600 kHz has been achieved using gate turn-off operation. Current sharing has been investigated in two- and three-device modules. Computer modeling of I-V data suggests that low conduction loss operation at very high current densities is achievable with improvements in ohmic contacts.

Device Structure and Fabrication

Thyristors were fabricated on highly doped (0001) Si-face 6H-SiC substrates obtained from Cree Research Inc. Three epitaxial layers were grown by Cree, to our specifications. All devices are pnpn structures. Two structures were investigated: devices with a p-type blocking layer, and devices with an n-type blocking layer. Both devices have gate contact made to the n-type epitaxally-grown layer adjacent to the anode layer.

Figure 1 shows the cross-section of the n-type blocking layer device. The n-type blocking layer is 6 μm thick. The p-type base layer is 2 μm thick, and the p-type anode layer is 1.5 μm thick. The blocking layer is lightly doped with nitrogen, $N_d = 4\text{-}5 \times 10^{15}$ cm^{-3}. Both p-type base layer and anode layer are doped with Al. Calculations based on blocking layer thickness and doping predict punch-through at 100V.

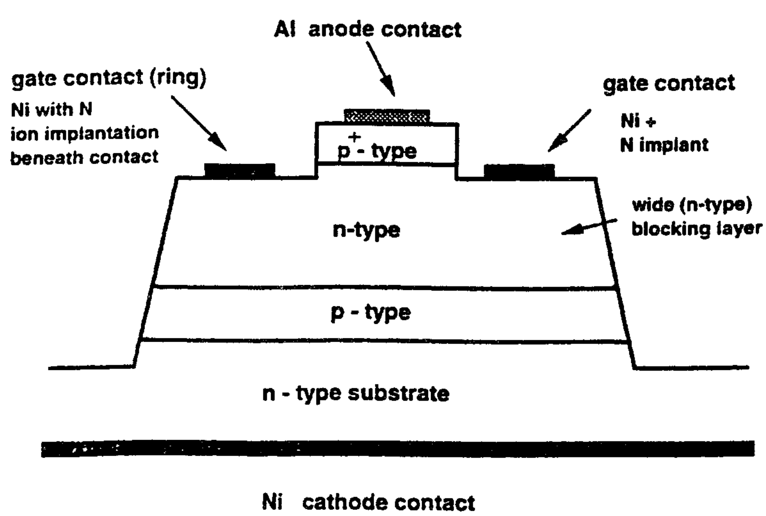

Figure 1. Cross-section of 6H-SiC thyristor with n-type blocking layer

The p-blocking layer device is similarly constructed. The blocking layer is thicker, 8 μm, and the n-type base layer is 2 μm thick. Calculations based on layer thickness and doping predict that these devices will hold-off approximately 600 V, before avalanche breakdown occurs.

Device are mesa-structure. Mesa diameter is .380 mm. The anode structure is formed by the gate recess etch. Anode diameter is 0.21 mm. The corresponding anode area, 3.46×10^{-4} cm^2 , is used for current density calculations. Gate recess and mesa etching were accomplished using a newly developed electron cyclotron resonant (ECR) plasma etch technique.

Relatively low-resistance contacts to highly doped n- and p-type SiC have been developed using nickel and aluminum , respectively. Ni was used for ohmic contact to the cathode. Aluminum was used for ohmic contact to the anode. Contacts were alloyed at 950 C in argon for 5 minutes. Specific contact resistance was measured by transmission line measurements (TLM). The specific contact resistances were $2\text{-}4 \times 10^{-4}$ ohm-cm^2 for the Ni contacts and $1\text{-}2 \times 10^{-3}$ ohm-cm^2 for the Al contacts.

Ni was used for gate contact metallization. Prior to metallization, the gate region was selectively implanted using N. The nitrogen implant was activated by annealing at 1250 C in argon for 30 minutes.

No passivations were used on these devices, however, measurements were taken with devices immersed in FC-40 fluorinert, to inhibit surface breakdown.

Etching

Silicon carbide is a difficult material to etch. For thyristors, deep etching (> 2 microns) is required for isolating devices (mesa etching) and for contacting the deeply-buried gate layer. No suitable wet chemical etch has been developed. Capacitively-coupled radio-frequency reactive-ion etching (rf-RIE) using flourine/oxygen-based gases has shown some promise [10] but suffers from low etching rates (30 nm/min.) and poor surface morphologies due to micromasking effects. High substrate potentials lead to high-energy ion bombardment which damages the semiconductor surface. Consequently, rf-RIE is adequate for shallow etching and cases where morphology and surface damage are not critical, but has drawbacks for the thyristor.

ECR etching was done using a Plasma-therm SL 700 reactor using a CF_4/O_2 mixture with 17.5% oxygen. Much faster etching (> 1200 angstroms/min), minimal damage, and excellent surface morphology [11,12] were demonstrated. The ECR process accomplishes this by creating a denser plasma at lower pressures. The substrate bias can be controlled independently of the plasma power. Lower substrate biases can be used, resulting in reduced surface damage from ion-bombardment.

Experimental

Thyristor switching measurements were taken under dc biased and pulsed bias conditions. Pulsed bias was applied using a low-impedance lab-built pulser. A pulse forming line circuit was used to characterize p-type blocking layer devices at high voltages (> 400 V).

In all measurements, the anode was grounded, and a negative bias was applied to the cathode. Devices were triggered by applying a negative pulse of approximately 5 V to the gate, through a selected current-limiting resistor.

A coaxial microprobe was used to contact the gate for fast measurements. A standard microprobe, made by Quatar Research, was used to ground the anode. Fast measurements were taken using a Tektronix 7104 oscilloscope. A LeCroy 9314M digitizing oscilloscope was used for routine measurements.

Switching Characterization

The room temperature I-V characteristic of a p-type blocking layer thyristor is shown in figure 2. The device shows the classic thyristor I-V. Data was taken point-by-point using an adjustable d.c. bias and 1 kΩ load resistor. The forward breakover voltage with zero gate current, was -160V. With a d.c. gate current of -50 μA, the forward breakover voltage was reduced to -130 V. At a current density of 361 A/cm^2 (124.9 mA), the forward voltage was -5.1 V. The holding current was -14.2 mA. Forward voltage at this current was -3.94 V.

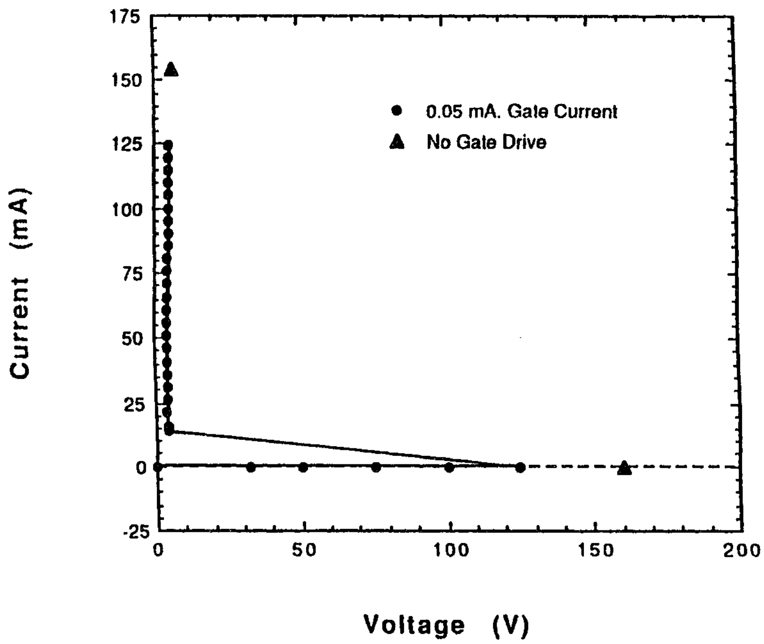

Figure 2 DC current-voltage characteristics of 6H-SiC thyristor with p-type blocking layer

Preliminary results on selected p-type blocking layer devices suggest the possibility of substantially higher voltage operation. The highest blocking voltage seen was over 600 V, shown in figure 3. The device showed self-turn-on at -650V, but was destroyed after operating for a few 100 μs at 200 kHz in a relaxation-oscillation mode.

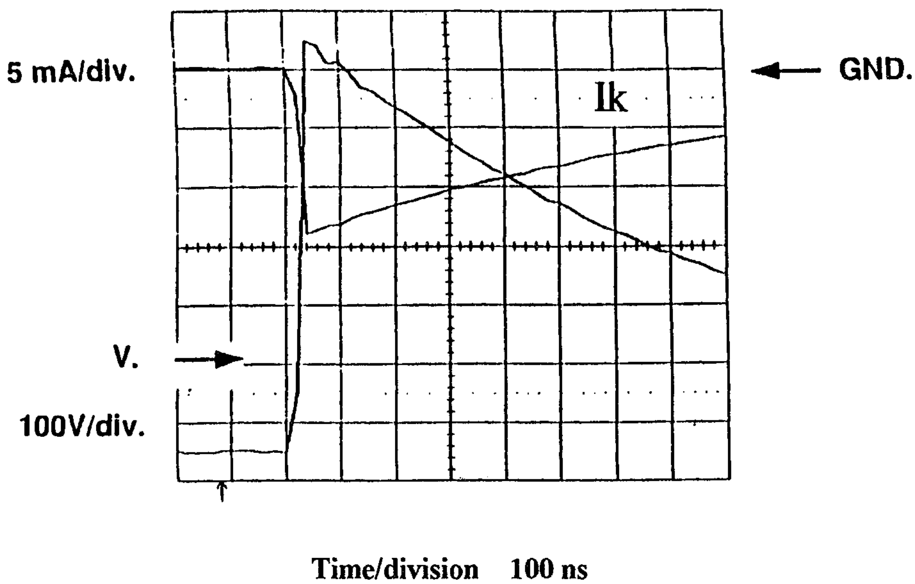

Figure 3. Anode voltage and cathode current switching waveforms for 6H-SiC thyristor with p-type blocking layer, showing 650 volt blocking voltage, and self-turn-on .

Typical turn-on waveforms for the n-type blocking layer devices are shown in figure 4. The rise time of the anode current is 43 ns. This rise time does not depend on the gate amplitude or rise time, but the delay between the application of the gate pulse and thyristor switching varies inversely with gate drive.

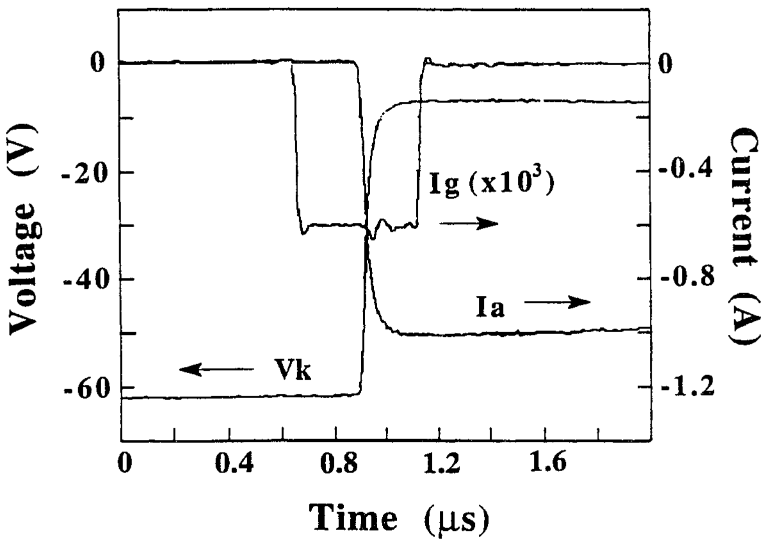

Figure 4. Turn-on switching waveforms of 6H-SiC thyristor with n-type blocking layer showing pulse-gated triggering

Figure 5 shows gate sensitivity. The n-type blocking layer devices can be triggered with less than 50 μA of gate current. Gate drive measurements reported by Cree Research on similar (pnpn) 6H-SiC thyristor structures are shown for comparison. The Cree thyristors require an order of magnitude higher gate drive.

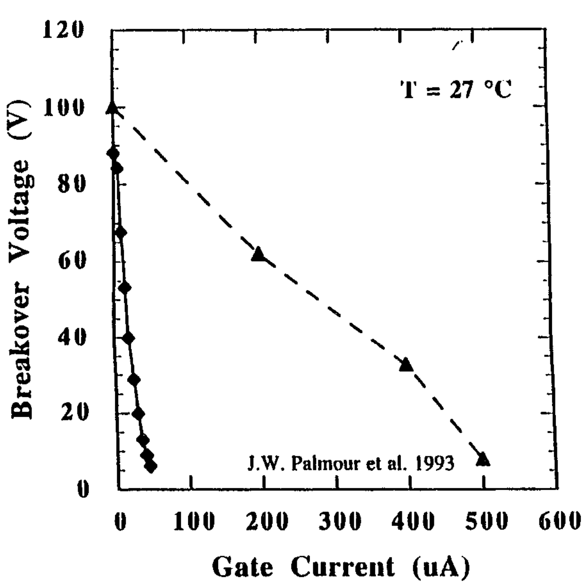

Figure 5. Breakover Voltage vs Gate Current for 6H-SiC Thyristors

Devices have operated reliably at very high current densities. Under a 250 μs bias pulse, a single n-type blocking layer device has conducted 1.80 A, over 5200 A/cm^2. Under a "quasi-dc" 1 s. bias pulse, devices have conducted 1.4 A, which corresponds to a current density of over 4000 A/cm^2. For comparison, silicon phase control and inverter grade thyristors are typically operated at current densities of 100-200 A/cm^2.

Figure 6 shows the current density vs. forward voltage characteristic for an n-blocking device over a wide range of current density. At 100 A/cm^2, the forward voltage drop is 2.9V. This is largely due to the built-in potential of the junction. At higher current densities, the forward voltage drop increases approximately linearly with current. At 500A/cm^2, the forward voltage drop is 3.6 V. At 2000 A/cm^2, it has increased to 6.4V. A computer simulation of the device, which uses the experimental data, is shown for comparison.. The simulation predicts the forward voltage characteristic for a device with lower anode contact resistance.

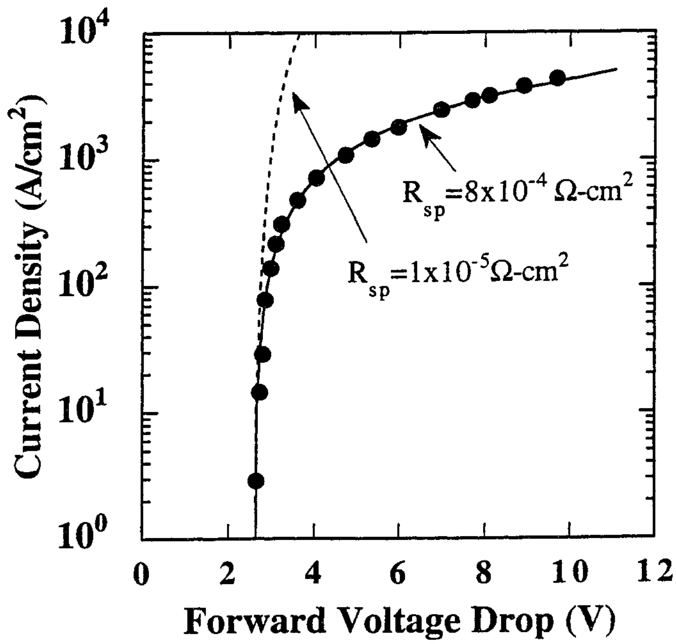

Figure 6. Measured (solid square) and calculated (solid and dashed lines) forward voltage drops as a function of device current density, for 6H-SiC thyristor with n-type blocking layer

High Frequency Operation

Due to fast risetime and short minority carrier lifetime[13], SiC thyristors may be capable of operation at much higher frequencies that silicon devices. We were able to effect high frequency operation using gate turn-off. The thyristor could be rapidly turned off by applying a reverse polarity gate pulse. Current fall time of less than 100 ns was observed. Devices operated up to 459 kHz at a 50% duty cycle, and 600 kHz at a 30% duty cycle. The turn-off current density was 30 A/cm^2. Gate turn-off at lower anode current showed a turn-off current gain as high as 5. The layout of the thyristor is far from optimal for gate turn-off operation, and optimization of the can be expected to significantly enhance gate turn-off performance.

Parallel Operation

Due to the presence of high concentrations of micropipe defects, devices are limited in size. As a result, switched currents are relatively low, in spite of high current density performance. To switch higher currents, selected devices were wire-bonded in parallel to build two- and three-thyristor modules. Current sharing and

switching speed were measured at room temperature ambient, but considerable self-heating occurred at high current densities.

The three-device module was subject to pulsed currents as high as 3.27 A. It withstood a 1 s. pulse at an average current density of 2475 A/cm^2, corresponding to 2.57A at t = 1second. At higher currents, bonding wires failed and the contact metallizations were damaged.

In the two-device module, current sharing was good at lower current densities, but degraded at higher current densities. At the highest current tested, 1.23 A (3.3 kA/cm^2), sharing was 46% /54% . Current sharing in the three device module was measured up to an average current density of 2.0 kA/cm^2, or 2.1 A. Over this range, current sharing was fair. A single device carried 25% - 35% of the total current. At the same forward voltage, the three device module conducts approximately three times the current as a single, isolated device.

Switching speed was somewhat degraded by packaging. Anode current risetime for a single device was approximately 70 ns. Current risetime for the three device module was approximately 80 ns.

High Temperature Operation

The operation of the n-type blocking layer thyristor was characterized at temperatures up to 300C.

Preliminary measurements show that the forward blocking voltage decreases only 4% as temperature is increased from room temperature to 300C. Over the same range, leakage current increased from approximately 10^{-5} A/cm^2 to 3.3×10^{-4} A/cm^2. Switching speed degrades. Switched current risetime increased from 43 ns at room temperature to approximately 60 ns at 300 C.

The temperature variation of forward voltage drop, shown in figure 7, depends on the current density. At current densities below 900 A/cm^2, the forward voltage drop is inversely proportional to temperature. At higher current densities, forward voltage drop increases with increasing temperature. This is favorable for parallel operation. Although the decrease in the built in potential with temperature dominates at low current density, increasing base resistance and contact resistance effects dominate at higher current densities.

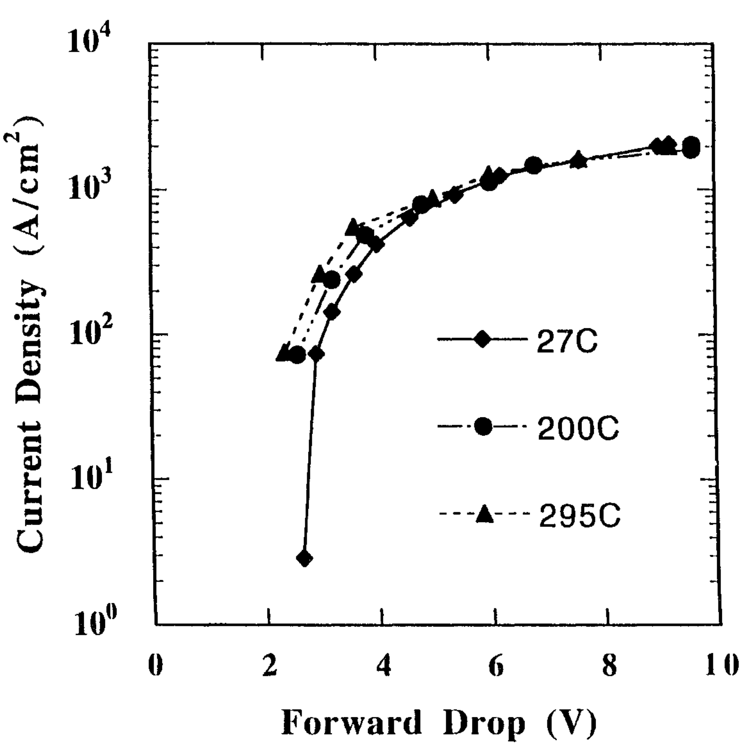

Figure 7. Variation of the forward voltage characteristic as function of temperature for 6H-SiC thyristor

Discussion

Advanced processing and fabrication techniques have been employed to make sensitive-gated, high-current density 6H-SiC thyristors capable of reliable operation at 300 C. Switching characteristics have been investigated at room temperature and at temperatures up to 300 C. Thyristors have been operated in parallel to obtain higher currents. High frequency gate turn off operation up to 600 kHz has been demonstrated

Two types of devices have been fabricated and tested: n-type blocking layer and p-type blocking layer.

The n-type blocking layer devices have demonstrated many desirable properties. Devices reliably block 100 V. An anode current risetime of 43 ns has been demonstrated. Devices have operated at very high current densities: over 5000 A/cm^2 under pulsed bias, and over 4000 A/cm^2 quasi-dc (1 s. pulse). These devices have switched the highest currents reported for any SiC thyristors; 1.8 A in a 250 μs pulse, and 1.4 A quasi-dc.

Preliminary measurements suggest that devices can be successfully paralleled to obtain higher current. Current sharing degrades at high current density, but remains within 6% of the ideal at current densities up to 2 kA/cm^2, in two-and three-device modules.

Gate turn-off operation, using a reverse polarity gate pulse, has been used to switch devices at high frequency. Devices operating at a current density of 30 A/cm^2 , have switched up to 600 kHz at a 30% duty cycle, and up to 498 kHz at a 50% duty cycle. This suggests a recovery time of approximately 1 microsecond before the device can be retriggered by this method. Device layout is not optimized for this mode of operation. An optimized design may be expected to result in higher turn-off current density.

High temperature operation was investigated. Devices operate reliably up to 300 C. Blocking voltage degrades only 4% from room temperature to 300 C. Leakage current at 300 C and -80 V, is .154 mA/cm^2. Switching speed degrades at higher temperatures, but remains below 100 ns. Gate sensitivity improves. At current densities below 900 A/cm^2, the forward voltage drop decreases with increasing temperature. However, at current densities above 900 A/cm^2, the forward voltage drop varies directly with temperature.

Preliminary results on p-type blocking layer devices suggest that operation up to 650 volts may be possible.

On-state conduction loss is a critical issue for power devices. It is, perhaps, the most significant drawback of silicon carbide junction devices. The computer simulation of the experimental data suggests that the large forward drop seen at high current densities is due to the contact resistance of the anode, and indicate a specific contact resistance of 8×10^{-4} Ω-cm^2. This is lower than the TLM measurements of the specific contact resistance, however, this may be explained by heating effects at the high switched currents [8]. The simulated forward voltage vs current characteristic is shown for an anode specific contact resistance of 1×10^{-5} Ω-cm^2. The simulation shows a much lower forward drop at high currents, and indicates that a forward voltage drop of only 3.3 V is possible at a current density of 5000 A/cm^2.

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